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Carbon-Based Nanoelectromechanical Devices**

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Keywords:
carbon nanotubes; carbon nanofibers; nanoelectromechanical systems; switch; varactor

Abstract

Carbon-based nanoelectromechanical devices are approaching applications in electronics. Switches based on individual carbon nanotubes deliver record low off-state leakage currents. Arrays of vertically aligned carbon nanotubes or nanofibers can be fabricated to constitute varactors. Very porous, low density arrays of quasi-vertically aligned arrays of carbon nanotubes behave mechanically as a single unit with very unusual material properties.

Introduction

The theoretical model predictions and experimental observations of actual response to electrical and mechanical stimuli of the carbon nanotube material family show that it is worthwhile to design and fabricate electronic devices using such materials. Advances for employing carbon nanotubes (CNTs) as conductors of current and/or heat in future integrated electronic systems have been extensively reported on and progress in that area has been rapid[1-3]. CNTs are also investigated in the role of acting as the active element in transistors[4,5]. With a broad perspective on electronics, carbon nanostructures have been demonstrated as an attractive choice as electrode material in sensor applications[6]. A different class of devices exploits the interplay between electrical and mechanical effects as the very key to the device functionality in a nanoelectromechanical system (NEMS). Although it is possible to conceive of many different devices and applications of NEMS made up of CNTs or similar materials, we focus our description on switches and varactors as model examples of such devices in this overview of recent advances towards the realization of carbon-based NEMS.

Modeling

By importing theoretically predicted[7] or measured values for the Young's modulus of CNTs[8] or carbon nanofibers (CNFs)[9] and by employing continuum mechanics in conjunction with analytical expressions or boundary element methodology we can couple the mechanical actuation to voltage induced electrical forces. In this way it is possible to make predictions of the behavior of electronic devices like switches and varactors. In the case of a switch, the basic functionality is to change conductivity from infinite to zero as fast as possible and with minimum cost of energy. One attractive feature of using CNT electromechanics to realize a switching device is that the small dimensions and high stiffness will give a high resonance frequency. This enables fast switching. Furthermore, the disjunct off-state of such a device will yield a leakage current that will give negligible contribution to the total power consumption of the device[10].

In the case of varactors the functionality is more complex than just achieving a transition from an on-state to an off-state. The geometry considered in this paper employs a pair of nanoelectromechanical electrodes to obtain the voltage dependent capacitance characteristic of varactors. These non-linear circuit elements find use e. g. in voltage controlled oscillators, and some of the critical features of the varactors are their capacitance per unit chip area and their swing in capacitance for the applicable voltage range. The modeling methods employed to describe these devices comprise boundary element calculations to resolve the geometrical effects on the nanostructures as well as simplistic analytical descriptions which can capture the qualitative behavior and give first order estimates of critical parameters.

Switches

In order to evaluate the optimal performance of digital switching devices fabricated using carbon nanotubes, a continuum mechanics approximation has been employed to describe mechanically switching beams of either multi-wall carbon nanotubes (MWCNT) or dense bundles of single-wall carbon nanotubes (SWCNT)[10]. The thickness of the beam, t, is a crucial design parameter among the geometrical dimensions where the beam length, L, and the nominal distance between beam and the actuating electrode, g_0, also play an important role. Figure 1 shows a schematic illustration of the geometrical configurations considered in the paper by Yousif et al.[10] and in Figure 2 the calculated threshold voltage to turn the switch on is displayed as a function of the beam length with the thickness as parameter for a given beam-contact gap of 2 nm and a beam width, W, of 8 nm. In order to optimize the geometry it is important to be able to control the beam thickness, i. e. the nanotube diameter or in the case of bundles, the number of nanotubes. Still, exploiting the freedom of the design space and assuming a high Young's modulus of 1 TPa, the carbon nanotube nanoelectromechanical switching will be more than one order of magnitude slower than a DRAM element at the same critical length (gate length and beam length). On the up side, the NEMS switch will consume orders of magnitude less power, mainly due to negligible off-state leakage current (1×10^{-5} μAμm^{-1} for CMOS DRAM and 1×10^{-9} μAμm^{-1} for the CNT switch). With a low actuation voltage design, the energy cost for a switching event can be in the aJ range[10].

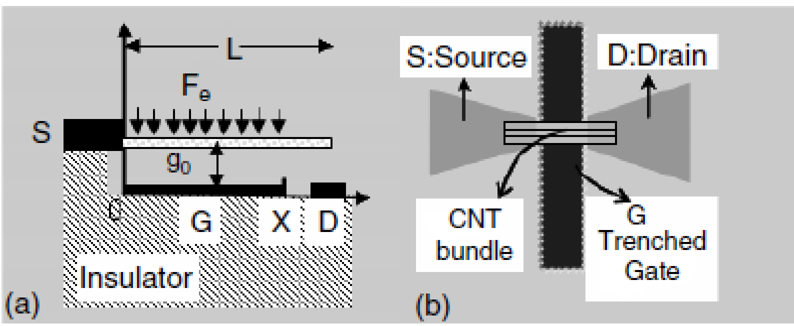

Figure 1. Schematic pictures of the (a) singly clamped and (b) doubly clamped configurations for a beam switch. From Yousif[10] reprinted with permission from IOP Publishing.

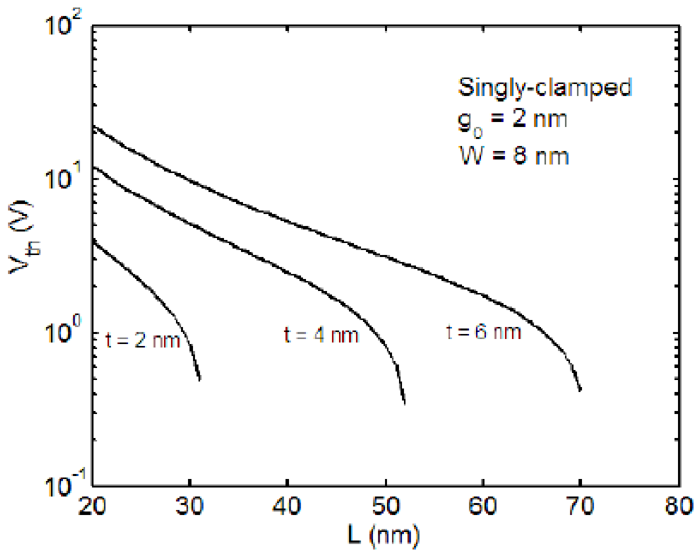

Figure 2. The dependence of the threshold voltage on the length of the switching beam. From Yousif[10] reprinted with permission from IOP Publishing.

Varactors

In the case of varactors one focus issue of the modeling we have employed is to correlate the effective Young's modulus of the NEMS with the experimentally measurable pull-in voltage – the minimum voltage required to bring the two electrodes of the capacitor into contact, forming an electrical short-circuit. In a simplistic lumped capacitance model, depicted in Figure 3, it is possible to arrive at an analytical relationship for the pull-in voltage as a function of the geometrical dimensions of the actuated electrode and of its effective spring constant, k[11]. Such a model is not powerful enough to faithfully resolve the interplay between pull-in voltage, geometry and stiffness of an individual NEMS element to the extent that we can understand e. g. the impact of growth conditions on its experimentally observed mechanical behavior. Using the boundary element method (BEM) in simulations[12] it is possible to obtain the deflection at a given geometry and biasing condition in an iterative fashion; the charge distribution is calculated first, then the resulting electric force, thereafter the deflection, after which the charge distribution (at the given voltage) is recalculated to start the next round of iteration. The outcome of such a simulation is displayed in Figure 4. In a design space delimited by estimations of experimentally relevant geometries, voltages and Young's moduli, the BEM simulations are run to generate a database of correlations between pull-in voltage and Young's modulus; a measurement of the pull-in voltage can then be directly correlated to a value of the Young's modulus for a given experimental condition, by referring to a generated relationship such as the one shown in Figure 5.

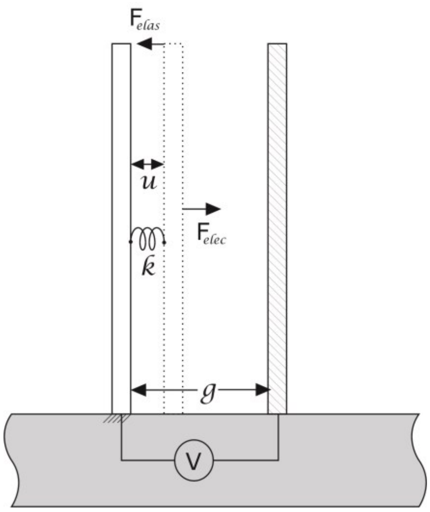

Figure 3. One-dimensional lumped model of the CNF varactor.

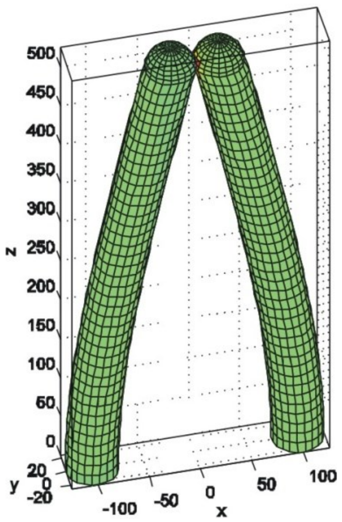

Figure 4. This image shows the result of applying the BEM to calculate the nanofiber deflection for a given applied voltage.

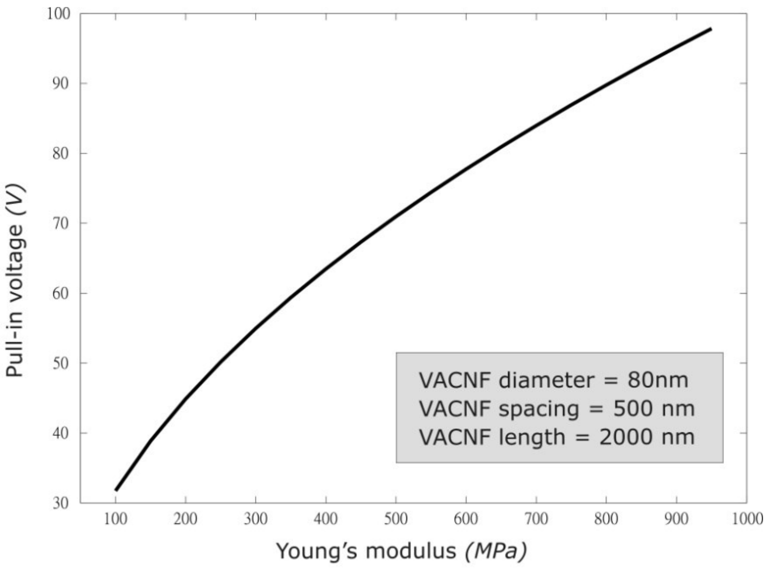

Figure 5. Resulting relationship between pull-in voltage and Young's modulus

Device Fabrication and Characterization

The technique of chemical vapor deposition (CVD) can produce CNTs and CNFs with a desired functional pattern. Any electronic function designed on a chip carries a cost in terms of its footprint, which makes it immediately favorable to design NEMS devices that extend upward, perpendicular to the chip surface. Depending on the processing details it is possible to obtain either individual free-standing vertically aligned CNFs (Figure 6) or forests of erect CNTs (Figure 7). In the case of CNFs the electric field of a plasma environment controls the growth directionality[13], whereas it is the interaction between CNTs grown at a high enough density and rate which induces the vertical alignment in the forest configuration[14]. The CNFs have a complex internal structure with less order than a nanotube[9], but one advantage is that individual vertically aligned nanostructures can be grown. It is not possible to achieve this with individual carbon nanotubes.

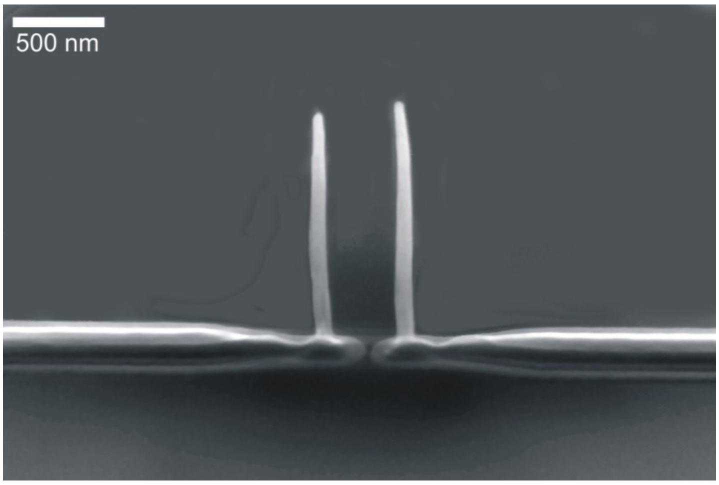

Figure 6. An SEM picture of a pair of individually contacted CNFs separated by a distance below 500 nm.

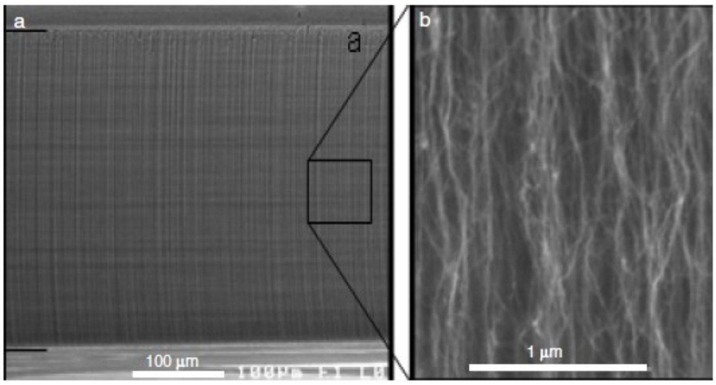

Figure 7. The forest of CNTs with a close up view to show the wiggly and porous structure. From Olofsson[16] reprinted with permission from IOP Publishing.

Individual Vertically Aligned Carbon Nanofibers

Electron beam patterned nanoscale Ni dots have been employed to catalyze the growth of nanofibers with a diameter of 100 nm and lengths exceeding 1 µm. Plasma CVD with a dc-plasma at a current of 20 mA was used to grow the fibers at 700 °C. The CNF pair of Figure 6 is an example of best achievement. The insulation between the individual fibers appears to be very good, with sub 0.1 nA current leakage up to 100 V. There is still need for further process optimization before we can fabricate single carbon nanofibers deterministically as a NEMS building block, but this development is on the level of optimization for specific processing tools, with the main hurdle being the choice of least interfering work-around to handle the discharging instabilities in the dc-plasma. Individual electrically addressable vertically aligned CNFs without mechanical degrees of freedom have been demonstrated[15].

Carbon Nanotube Forest

Using thermal CVD at 700 °C with Fe catalyst, forests of vertically aligned 135 µm high multiwalled carbon nanotubes have been grown with a length of 200 µm, a width of 4 µm and a lateral separation of 10 µm[16]. The areal density of nanotubes in the forest was estimated at 10^{10} nanotubes cm^{-2}, and matching simulations to the measured actuation of these varactor electrodes yielded an effective Young's modulus on the order of a few MPa, i. e. far below the TPa often attributed to individual nanotubes, thus allowing actuation to be achieved for relatively low applied voltages[16]. The very low effective Young's modulus can be attributed to the highly porous and "wiggly" nature of the material (Figure 7). A varactor device designed using this material is displayed in Figure 8, showing the buttresses that need to be added to achieve sufficient mechanical rigidity. In Figure 9 the degree to which capacitance tuning can be achieved is shown along with the consequence of exceeding the pull-in voltage, as illustrated by two SEM images after the catastrophic event, which also alters the capacitance-voltage characteristic. The capacitance was determined by matching S parameter simulations to measurements, using an equivalent circuit which gave very good agreement with experimental observations[17].

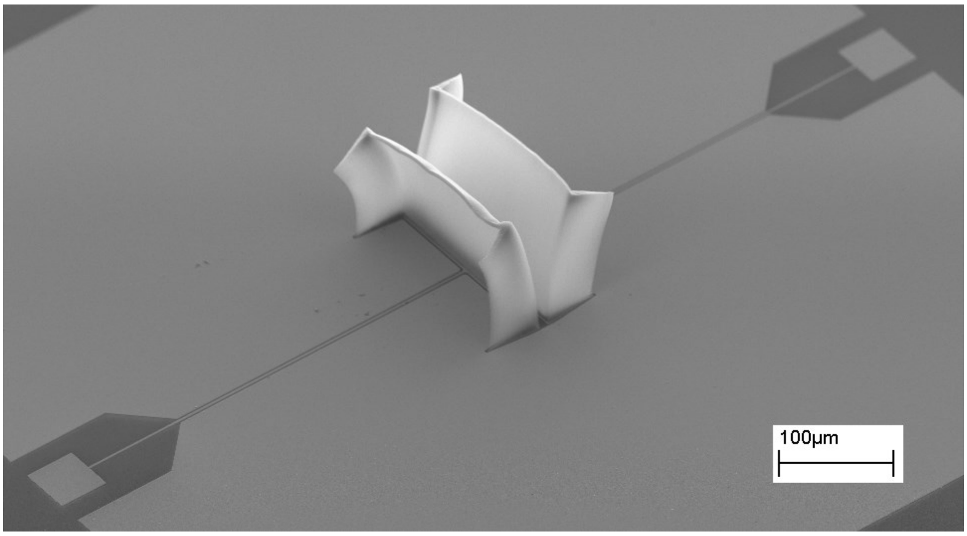

Figure 8. Varactor electrodes made by carbon nanotube forests. Reprinted from Ek-Weis[17] with permission from Professional Engineering Publishing.

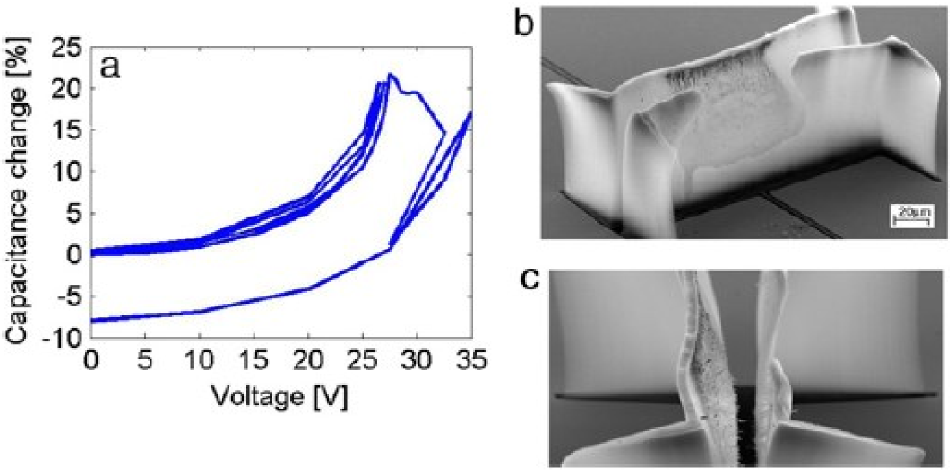

Figure 9. a) Capacitance change as a function of voltage; b) and c) SEM images of the structure after exceeding pull-in. From Olofsson[16] reprinted with permission from IOP Publishing.

CMOS Compatibility

It is a very attractive goal to be able to harness the advantages of carbon-based NEMS on a conventional CMOS electronics platform. Integration is a crucial issue when aiming for competitive system level performance for devices that incorporate and utilize NEMS.

However, finding a way to match the processing requirements to obtain good carbon nanostructures with the restrictions for processes and materials in CMOS production is not trivial. The outcome of exposing transistors fabricated in 130 nm bulk CMOS technology to carbon nanofiber growth conditions, i. e. elevated temperatures and a plasma environment, shows that transistors can survive such a treatment and even perform without immediate detrimental consequences. Comparing rf-plasma processing at 560 °C, thermal CVD at 610 °C and exposure to a dc-plasma at 500 °C, the last of these three nanofiber growth methods gives the least impact on transistor performance[18], and in the case of the on-state drain current there is no discernible effect, as is shown in Figure 10.

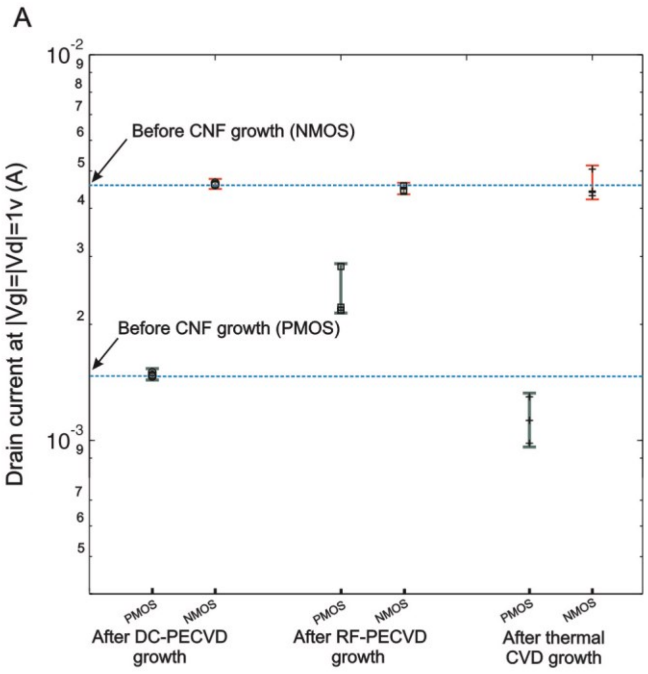

Figure 10. Deterioration of the on-state drain current of PMOS and NMOS transistors after three disparate growth processes. From Ghavanini[18]; reprinted with permission from ACS Publications.

Conclusion

In theory, carbon-based nanoelectromechanical switches can provide a low static power technology with potential for high frequency operation. Components constituted by carbon nanotubes will display high mechanical stability and will also be highly stable with regards to temperature. However, the dependencies of device properties like these on the specific growth conditions need further investigations. Large scale reproducible and reliable manufacturing of integrated NEMS elements remains extremely challenging, where growth on top of CMOS as a back-end process further increases the complexity and limits the degrees of freedom by having to resolve the conflict between CMOS compatibility requirements and carbon nanostructure quality; this integration scenario is still however a future possibility albeit not obviously achievable.

CNT-based NEMS switches demonstrate very low off-state leakage currents. Varactors can be realized with individual vertically aligned CNFs or with walls consisting of quasi-vertically aligned arrays of sparse CNTs. The latter are very porous, but behave mechanically as a cohesive unit with exceptional material properties.

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